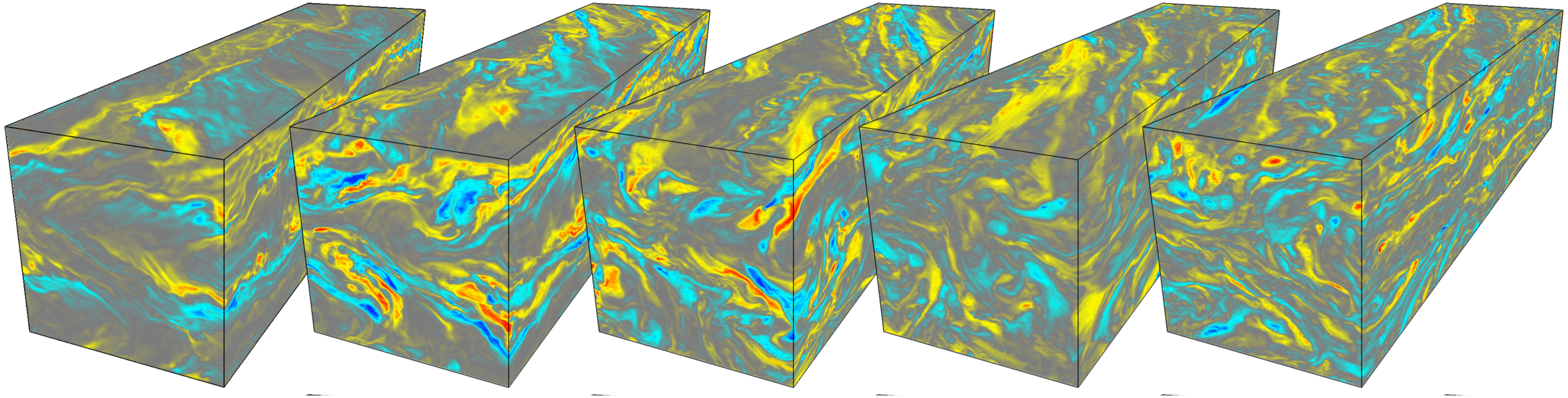
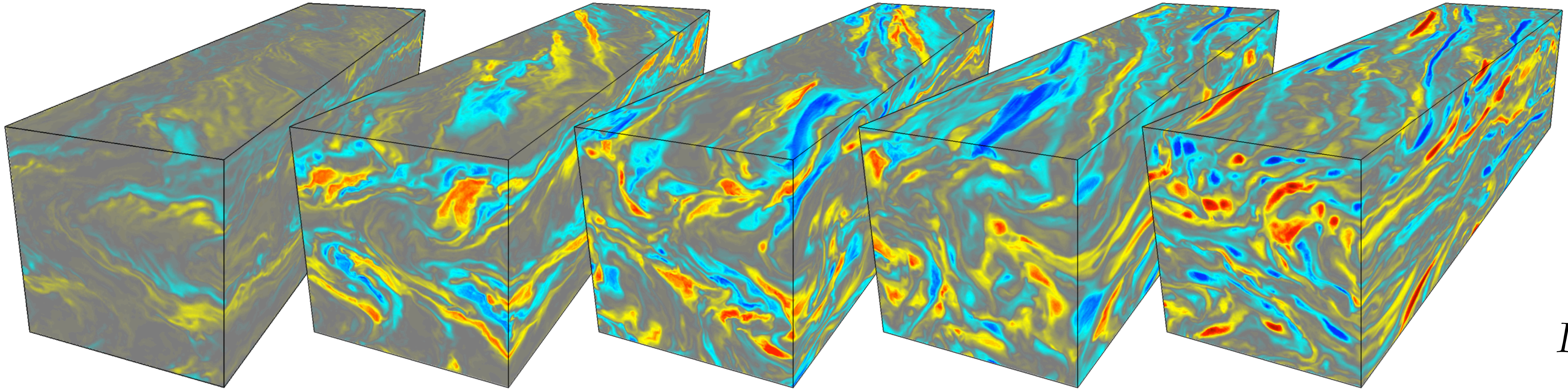


Magnetorotational Turbulence and Dynamo in a Collisionless Plasma

Matthew Kunz
Princeton University

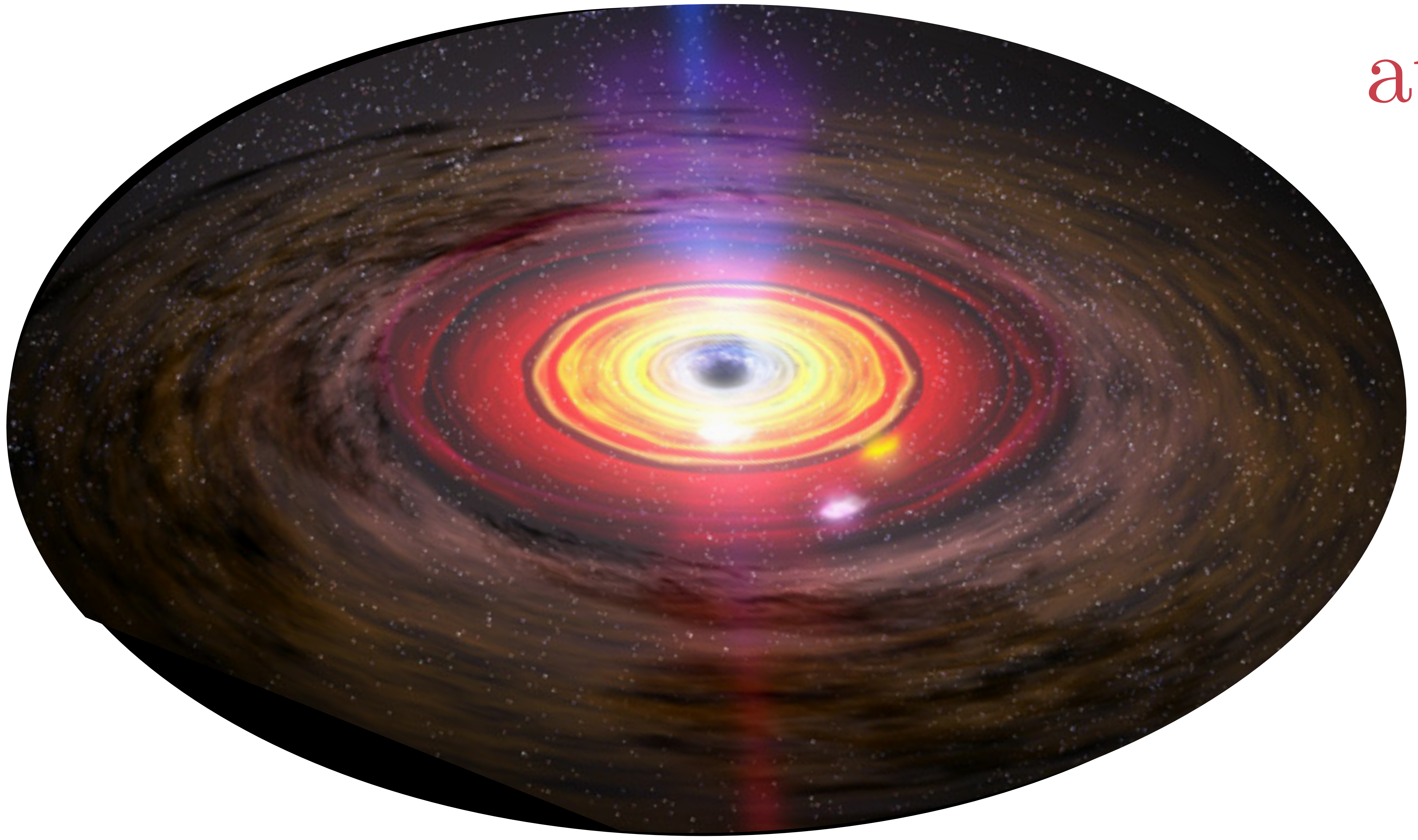
Jim Stone
Princeton University

Eliot Quataert
U. California, Berkeley



Phys. Rev. Lett. **117**, 235101(2016)

Low-luminosity black-hole accretion flows are weakly collisional



e.g., Galactic center Sgr A*

at $R \sim 0.1$ pc... (~10^5 R_{horizon})

$n \sim 100 \text{ cm}^{-3}$ $\lambda_{\mathrm{mfp}} \sim 0.01$ pc

$k_B T \sim 2$ keV $\rho_i \sim 1$ ppc

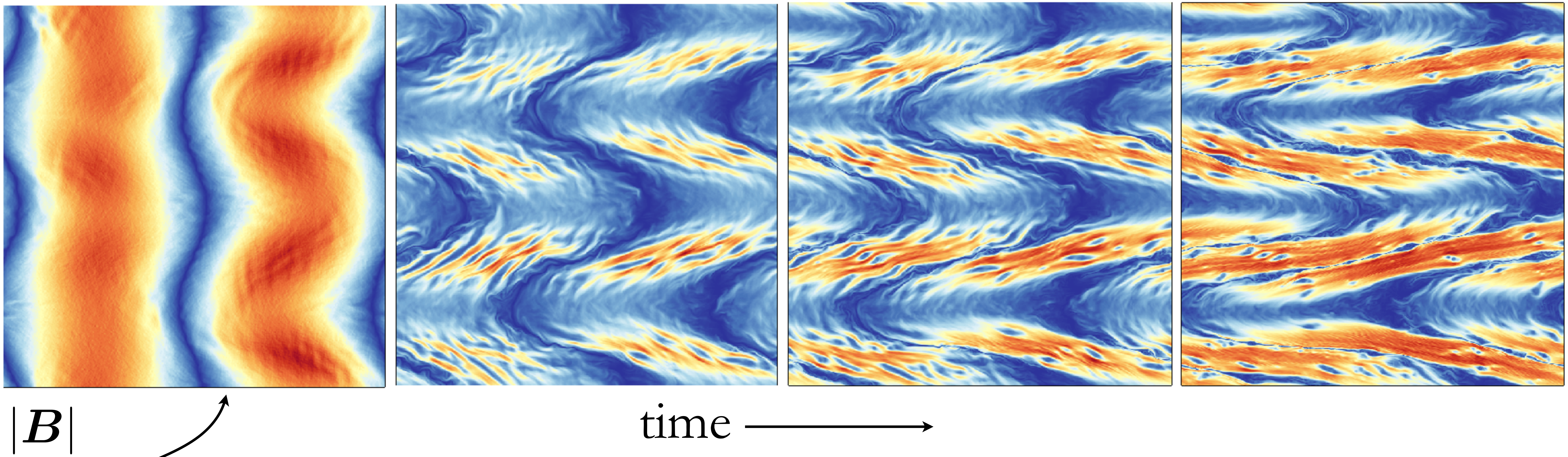
$B \sim 1$ mG $\Omega_i \sim 10 \text{ s}^{-1}$

becomes collisionless within this radius

a **kinetic** approach is thus necessary to understand:

- transport of heat and angular momentum
- particle energization
- growth and structure of magnetic field

Magnetorotational Instability (MRI) amplifies magnetic fields and drives angular-momentum transport, even in collisionless plasmas



demonstration of MRI “channel modes” in collisionless plasma

new feature: MRI drives pressure anisotropy, which triggers kinetic instabilities

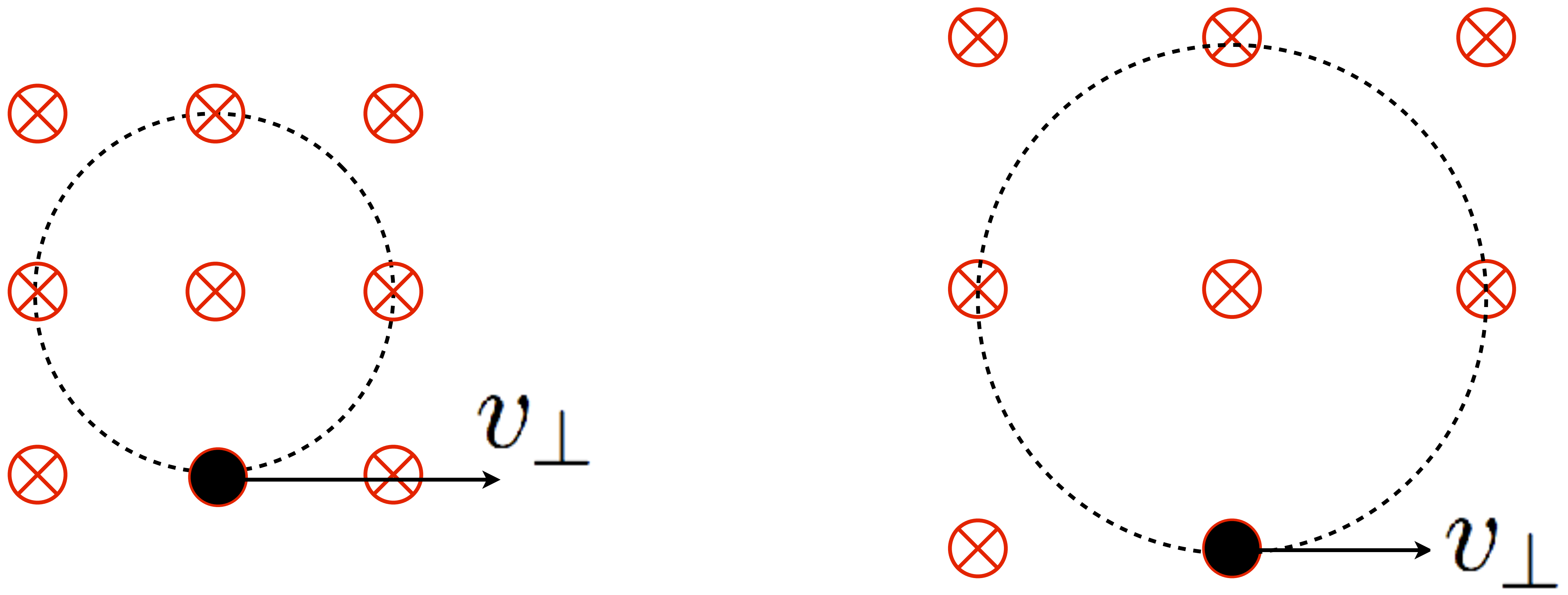
see Riquelme et al. 2012 & Hoshino 2013 for more on kinetic MRI in 2D

Change magnetic-field strength, generate velocity-space anisotropy…

adiabatic invariants: $$\frac{\mathrm{d}}{\mathrm{d}t}\oint \boldsymbol{p}\cdot\mathrm{d}\boldsymbol{q} \simeq 0$$

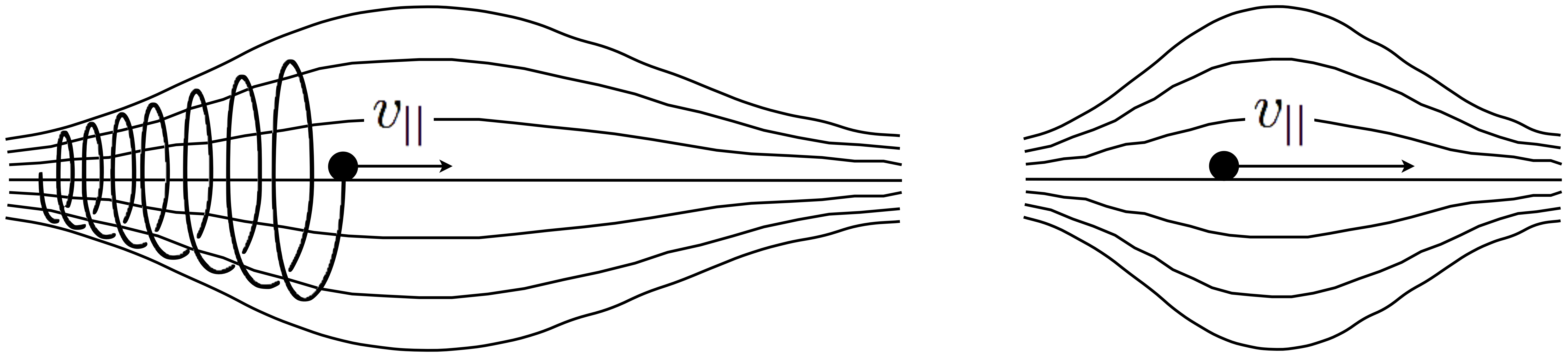
$$\mu = \frac{mv_\perp^2}{2B}$$

Kruskal (1958)



$$J = \oint \mathrm{d}\ell_{\mathrm{B}}\, mv_{||}$$

Northrop & Teller (1960)

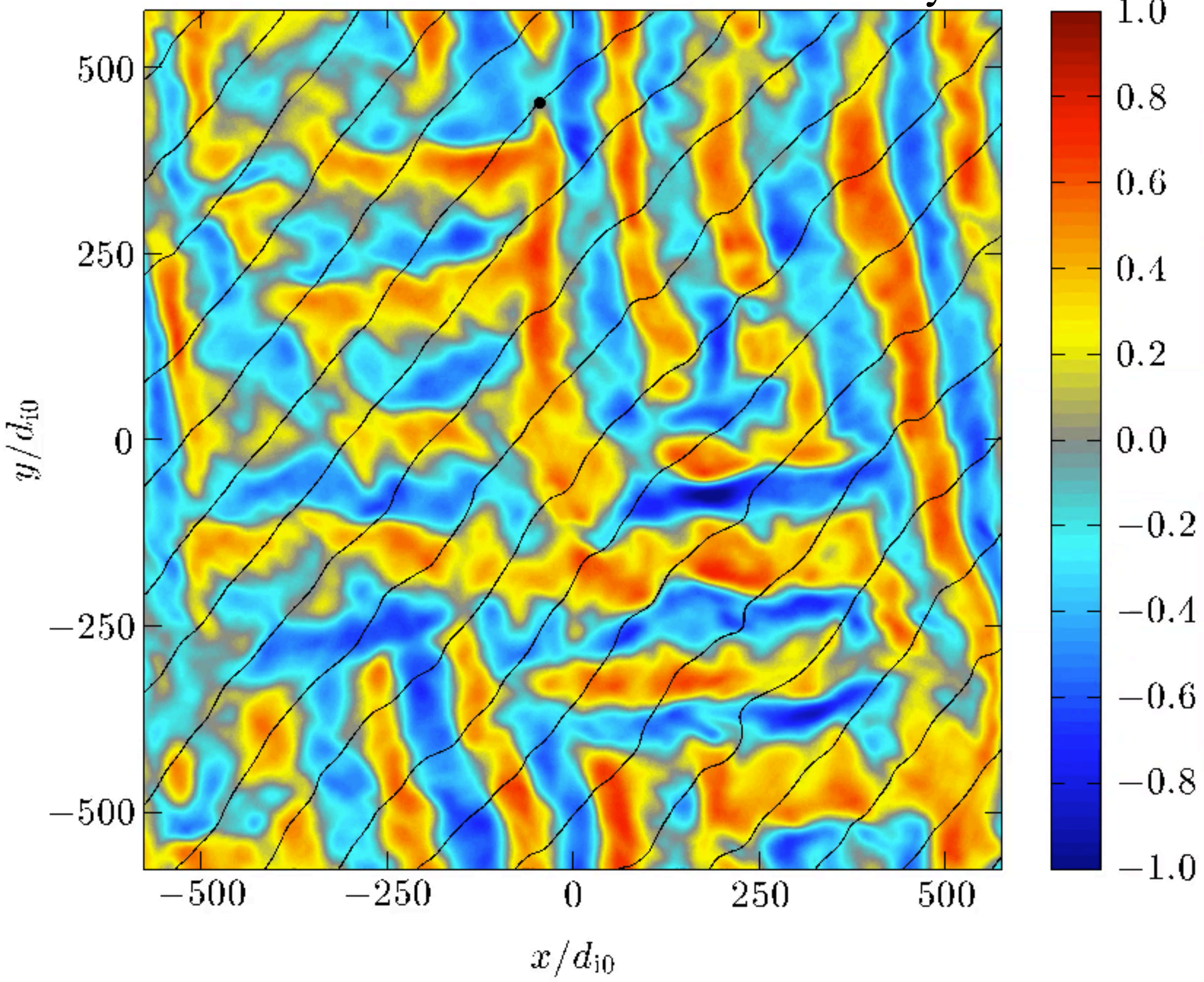


field-biased **pressure anisotropy** is important:

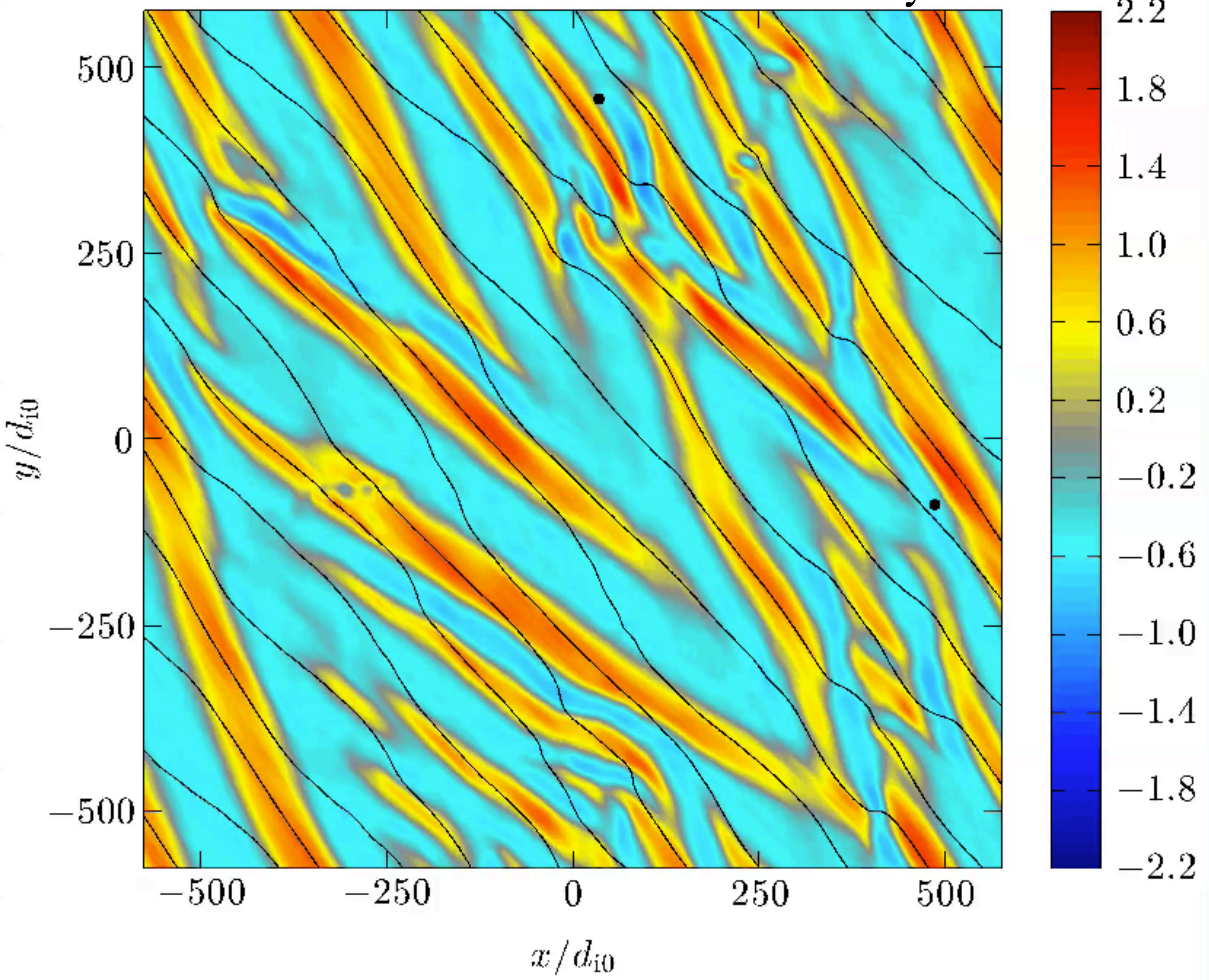
- triggers Larmor-scale instabilities, which set effective viscosity (and conductivity)

Kunz, Schekochihin & Stone (2014), *Phys. Rev. Lett.*

driven firehose instability



driven mirror instability



field-biased **pressure anisotropy** is important:

- modifies linear MRI (Quataert, Dorland & Hammett 2002), nonlinear MRI (Squire, Quataert & Kunz 2017), and MRI turbulence (Sharma et al. 2006)

stress transporting angular momentum:

$$T_{R\phi} = \underbrace{\rho u_R u_\phi}_{\text{Reynolds stress}} - \underbrace{\frac{B_R B_\phi}{4\pi}}_{\text{Maxwell stress}} \left(1 + \underbrace{\frac{p_\perp - p_\parallel}{B^2/4\pi}}_{\text{“viscous” stress}} \right)$$

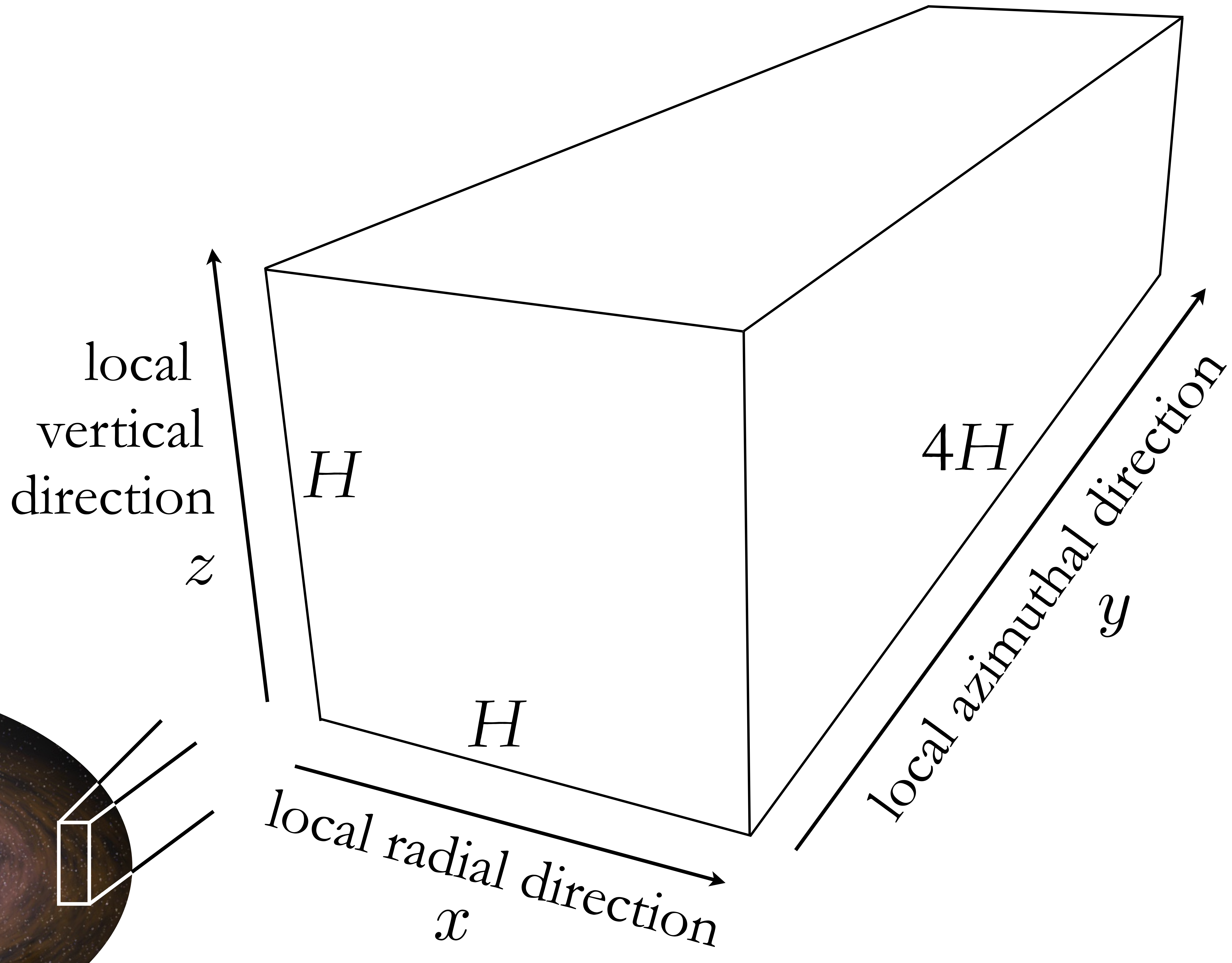
hybrid-kinetic PIC shearing-box simulation
of 3D3V magnetorotational turbulence
and dynamo, using *Pegasus*

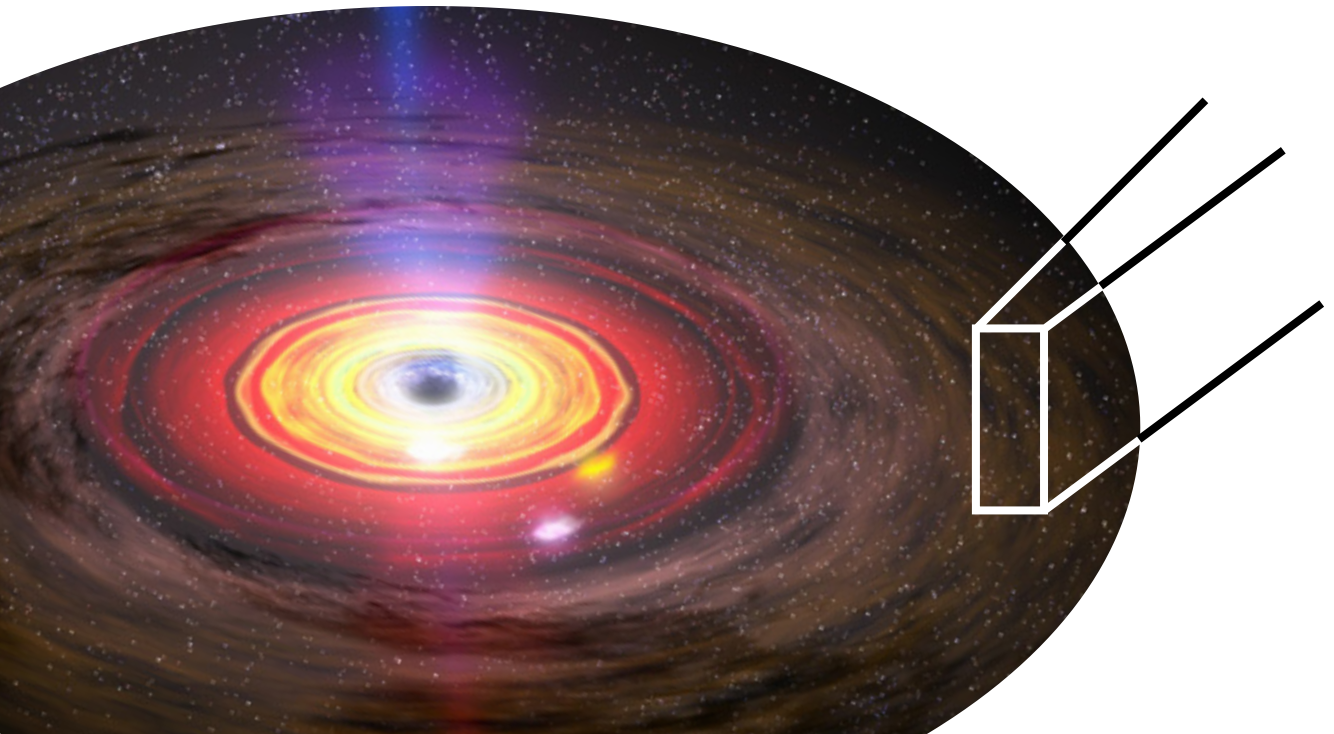
(Kunz, Stone & Bai, *J. Comp. Phys.* 2014)

$$H \doteq \frac{v_{\rm th}}{\Omega_{\rm rot}} = 50 \text{ initial ion Larmor radii}$$

$$\beta_0 = 400 \quad \text{zero-net flux}$$

$$\mathrm{Rm} \doteq \Omega_{\rm rot} H^2/\eta = 37,500$$





384 x 1536 x 384 cells
with 14.5 billion particles

$$\left(\frac{\partial}{\partial t}-\frac{3}{2}\Omega_{\rm rot}x\frac{\partial}{\partial y}\right)f+\boldsymbol{v}\boldsymbol{\cdot}\boldsymbol{\nabla}f+\left[\frac{Ze}{m}\left(\boldsymbol{E}+\frac{\boldsymbol{v}}{c}\times\boldsymbol{B}\right)-2\Omega_{\rm rot}\hat{\boldsymbol{e}}_z\times\boldsymbol{v}+\frac{3}{2}\Omega_{\rm rot}v_x\hat{\boldsymbol{e}}_y\right]\boldsymbol{\cdot}\frac{\partial f}{\partial\boldsymbol{v}}=0$$

$$\boldsymbol{E}+\frac{\boldsymbol{u}}{c}\times\boldsymbol{B}=-\frac{T_e}{e}\boldsymbol{\nabla}\ln n+\frac{(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B}}{4\pi Zen}$$

$$\left(\frac{\partial}{\partial t}-\frac{3}{2}\Omega_{\rm rot}x\frac{\partial}{\partial y}\right)\boldsymbol{B}=-c\boldsymbol{\nabla}\times\boldsymbol{E}-\frac{3}{2}\Omega_{\rm rot}B_x\hat{\boldsymbol{e}}_y$$

Questions to address:

1. What is the nonlinear saturated state of the MRI in a collisionless plasma?

2. How is marginal stability to kinetic instabilities achieved and maintained as the MRI amplifies the magnetic field?

3. What is the effective viscosity (and conductivity) in these disks? What role does collisionless wave damping play in limiting the efficacy of large-wavelength modes to transport angular momentum?

4. Connection between angular-momentum transport and particle heating?

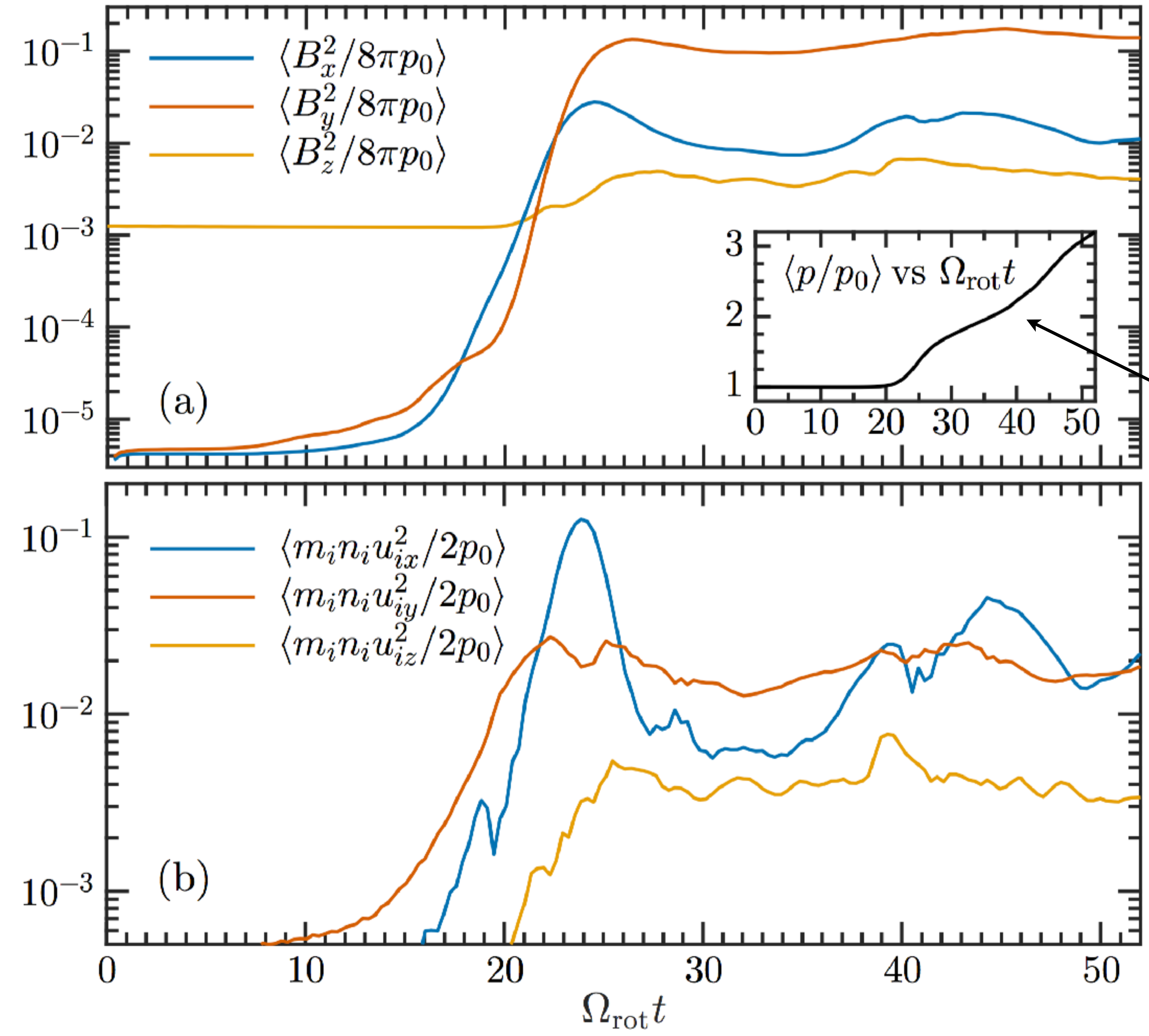
5. How do these properties vary with radius and height in a global setting?

radial magnetic field
(times 2)
azimuthal magnetic field
z
y
x
−40 −30 −20 −10 0 10 20 30 40
(in units of B_0)

box-averaged energies vs. time

magnetic energy
(azimuthal dominates)

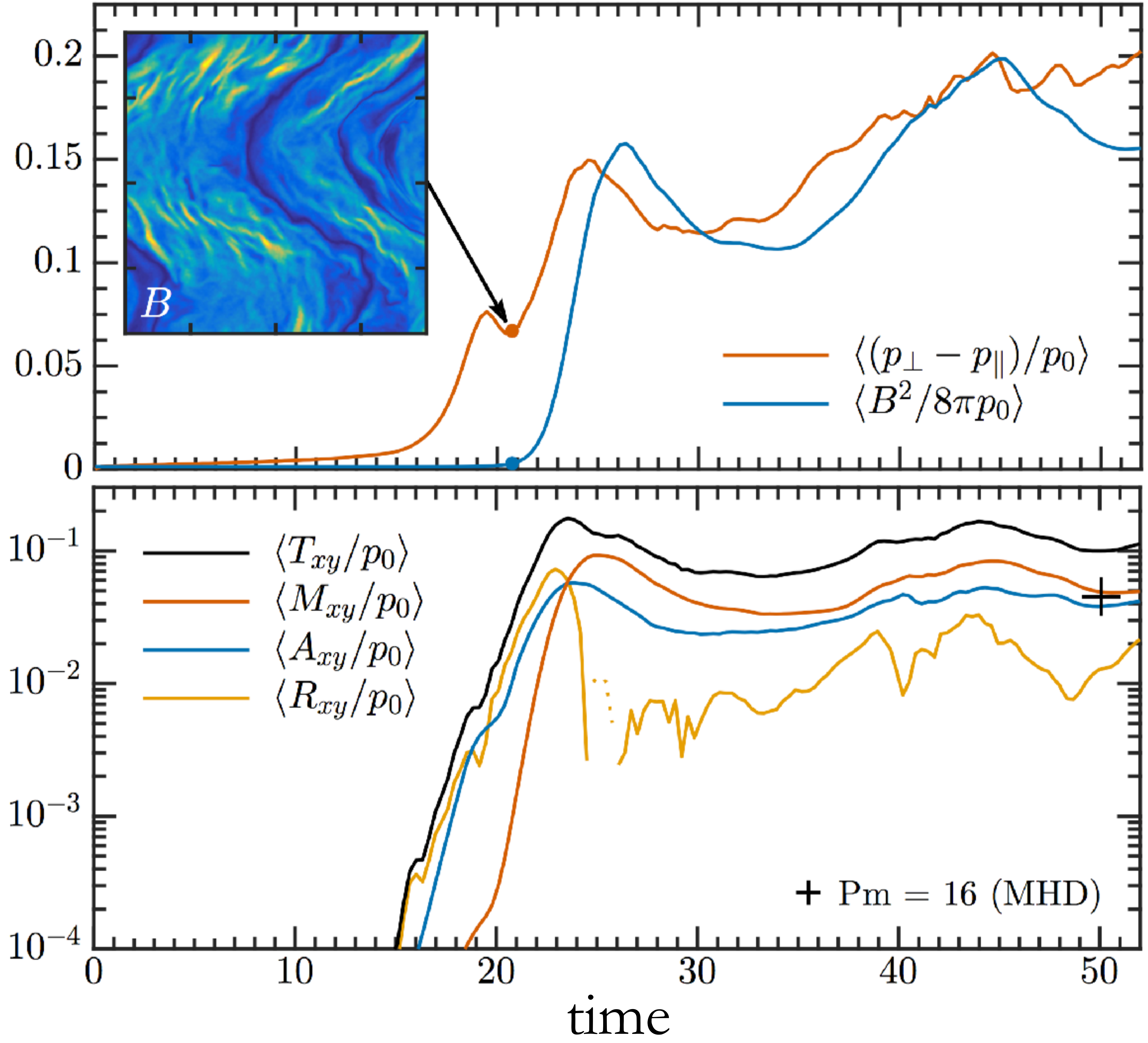
kinetic energy



thermal
pressure

MRI drives **pressure anisotropy**, triggers mirror modes, **regulate** pressure anisotropy

(time lag related to insufficient scale separation …more later)



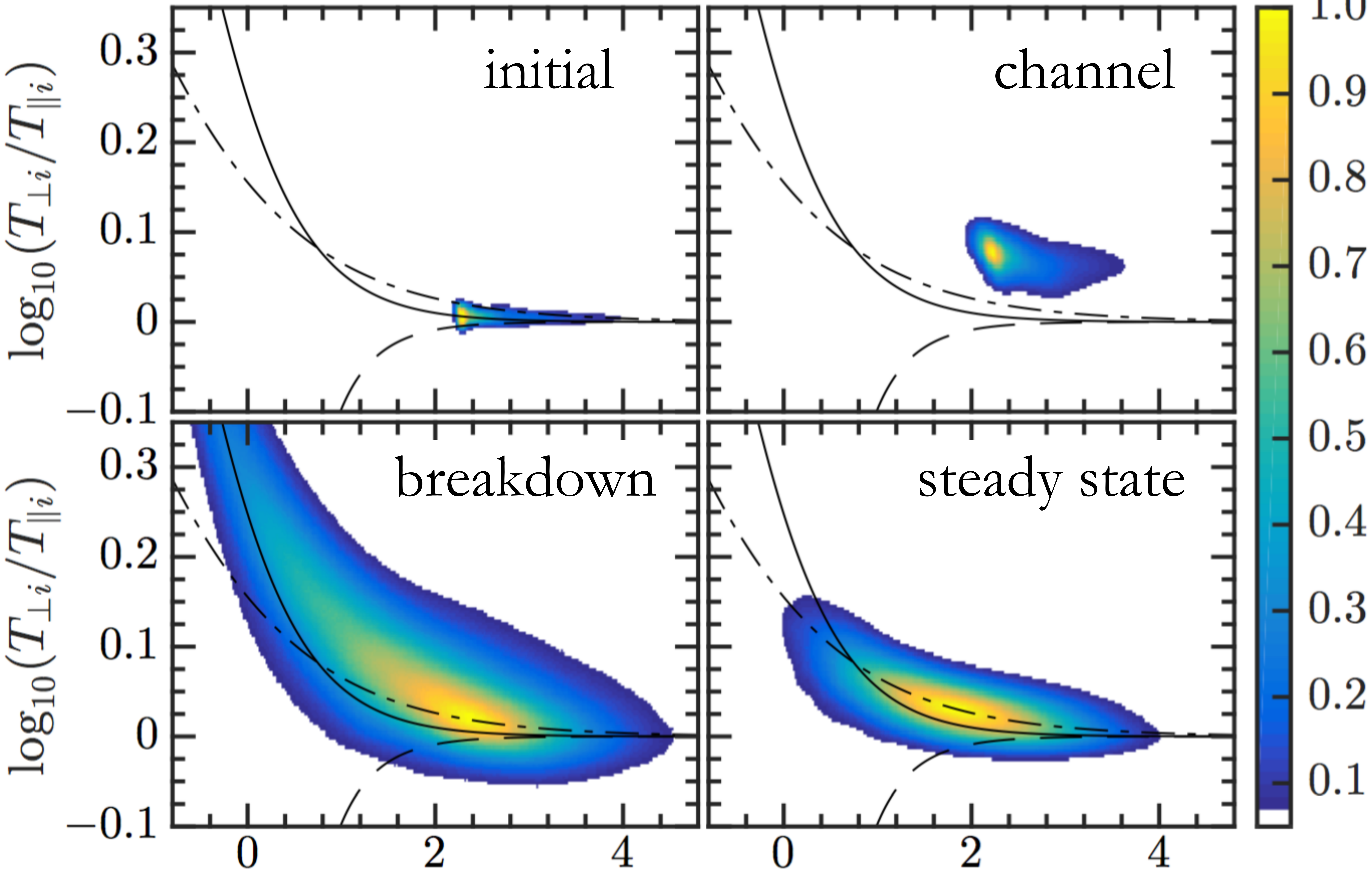
angular-momentum transport due to **pressure anisotropy** is comparable to (usual) transport by **Maxwell stress**

direct connection between plasma micro-physics and macro-scale dynamics

histogram of simulation data

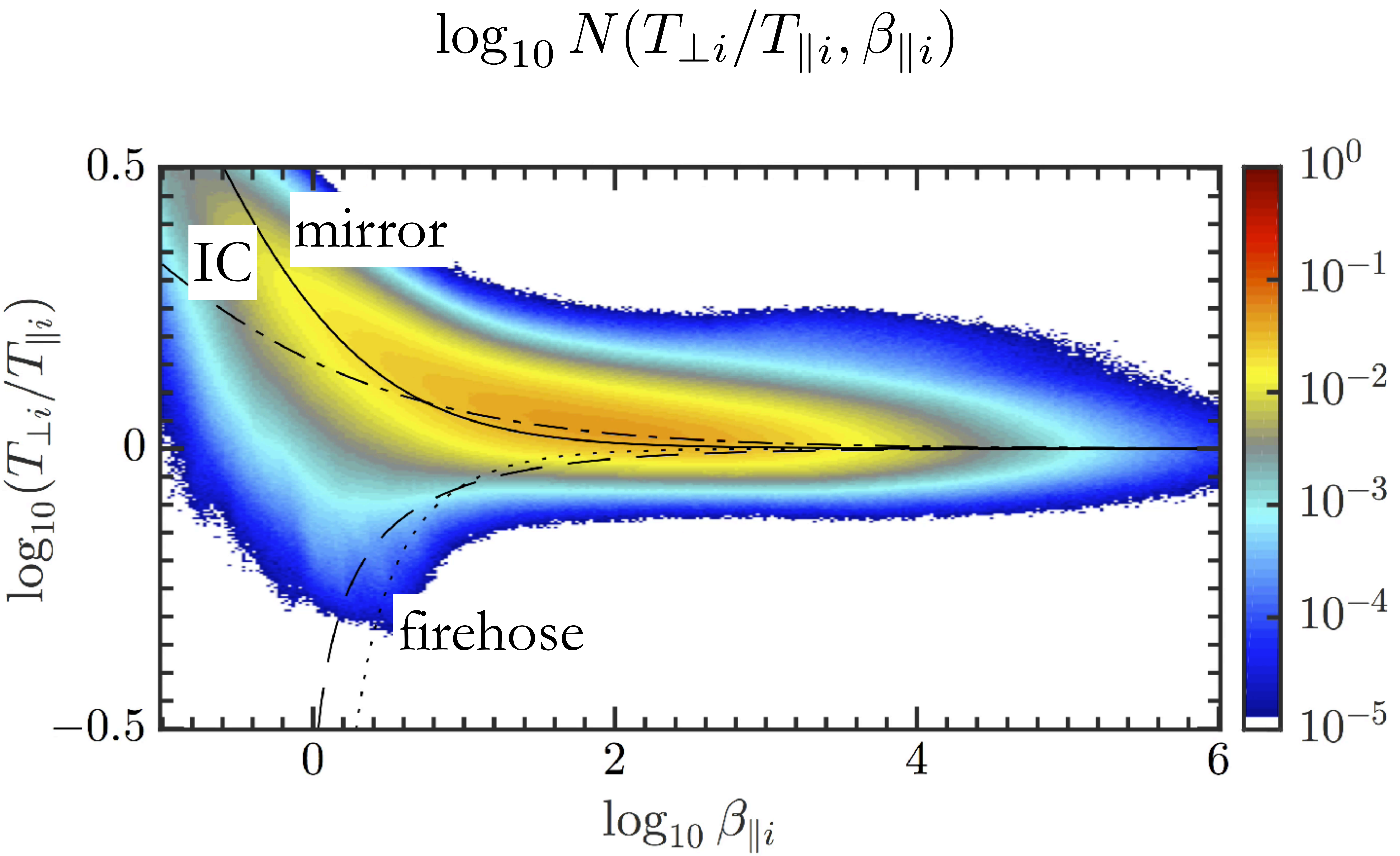
log(ion pressure anisotropy)

(0 = isotropic)



log(ion plasma beta)

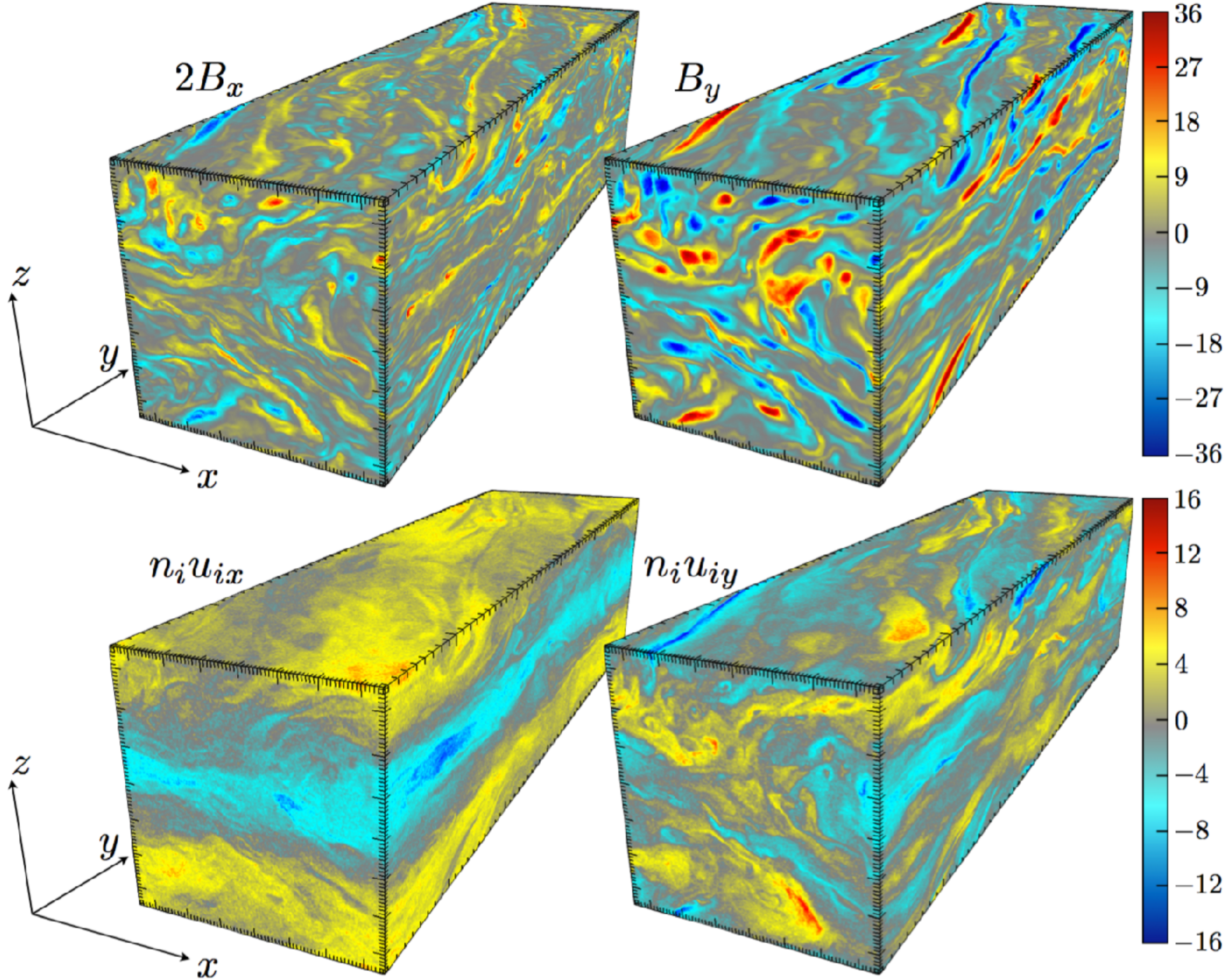
solid line is the mirror instability threshold


$\log_{10} N(T_{\perp i}/T_{\parallel i}, \beta_{\parallel i})$
mirror
IC
firehose
$\log_{10}(T_{\perp i}/T_{\parallel i})$
$\log_{10} \beta_{\parallel i}$
0.5
0
−0.5
0
2
4
6
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

radial and azimuthal magnetic-field fluctuations

radial and azimuthal (ion) momentum fluctuations

behaves like a Pm >> 1 plasma



Energy vs. wavenumber

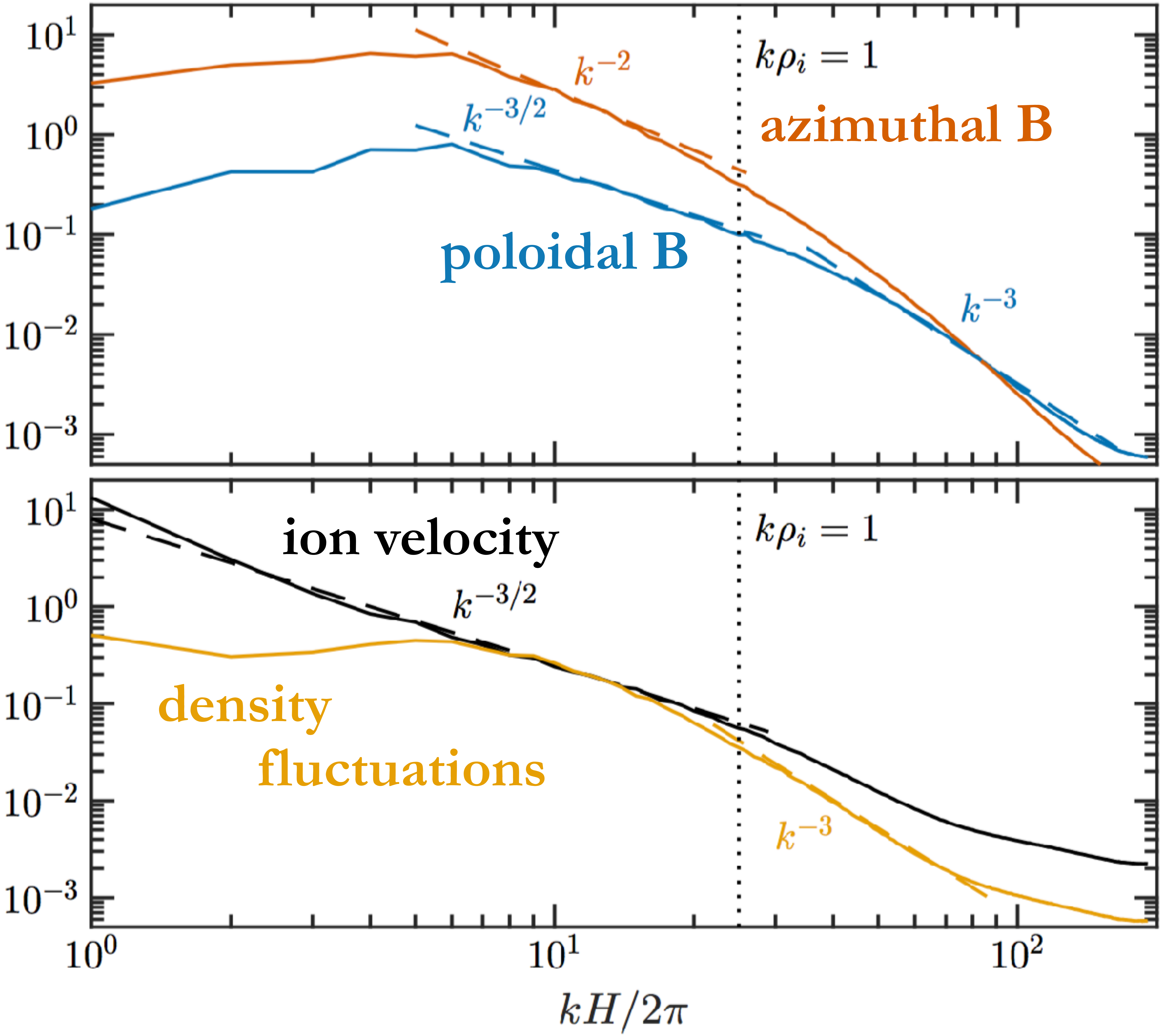
$$k\rho_i < 1$$

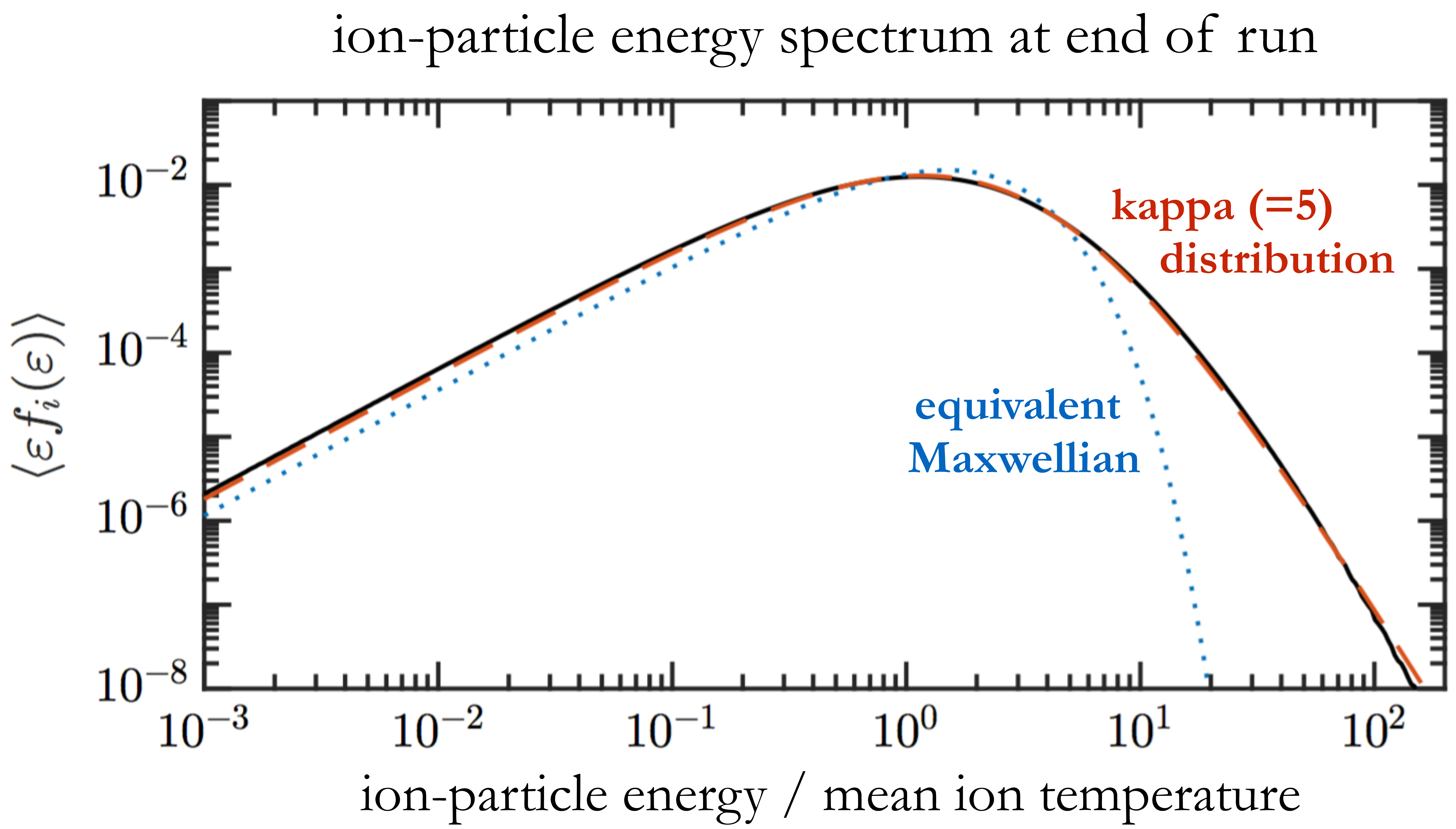
similar to MHD studies
(e.g., Walker, Boldyrev & Lesur 2016)

Alfvén-wave cascade along locally azimuthal "guide" field

$$k\rho_i > 1$$

kinetic-Alfvén-wave cascade
(-3, like in solar wind)





ion-particle energy spectrum at end of run
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$\langle \varepsilon f_i(\varepsilon) \rangle$
kappa (=5)
distribution
equivalent
Maxwellian
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
ion-particle energy / mean ion temperature

Profits, Perils, and Price (of our approach)

Profits: First 3D3V kinetic simulation of magnetorotational turbulence and dynamo — *feasible!*

Ab initio demonstration that pressure anisotropy enhances angular-momentum transport in a way controlled by the kinetic microphysics

Despite the absence of (explicit) interparticle collisions, much at large scales looks like (anisotropic, Pm >> 1) MHD

Can afford good scale separation, which can capture both Alfvénic and kinetic-Alfvén-wave cascade

Profits, Perils, and Price (of our approach)

Perils:

Massless, isothermal, fluid electrons (can improve this)

No electron heating included (can improve this)

More scale separation and orbits would be better

Price:

$$\mathrm{cost} \propto (k_{\max}\rho_{i0})^4 \left(\frac{\Omega_{i0}}{\Omega_{\mathrm{rot}}}\right)^{-4} \quad \ldots\text{ouch}$$

BUT, doing fully kinetic with

$m_i/m_e = 25 \quad c/v_{th,e} = 5 \quad \Delta x = \lambda_{\mathrm{D}}/2$

4 particles per cell and all else the same

$\sim 10^{12}$ CPU-hours per orbit!

Conclusions

(1) Micro-scale physics can play a fundamental role in dictating what macro-scale dynamics are allowed in a given system;

(2) 3D kinetic simulations of magnetorotational turbulence and plasma dynamo are now within reach (though expensive);

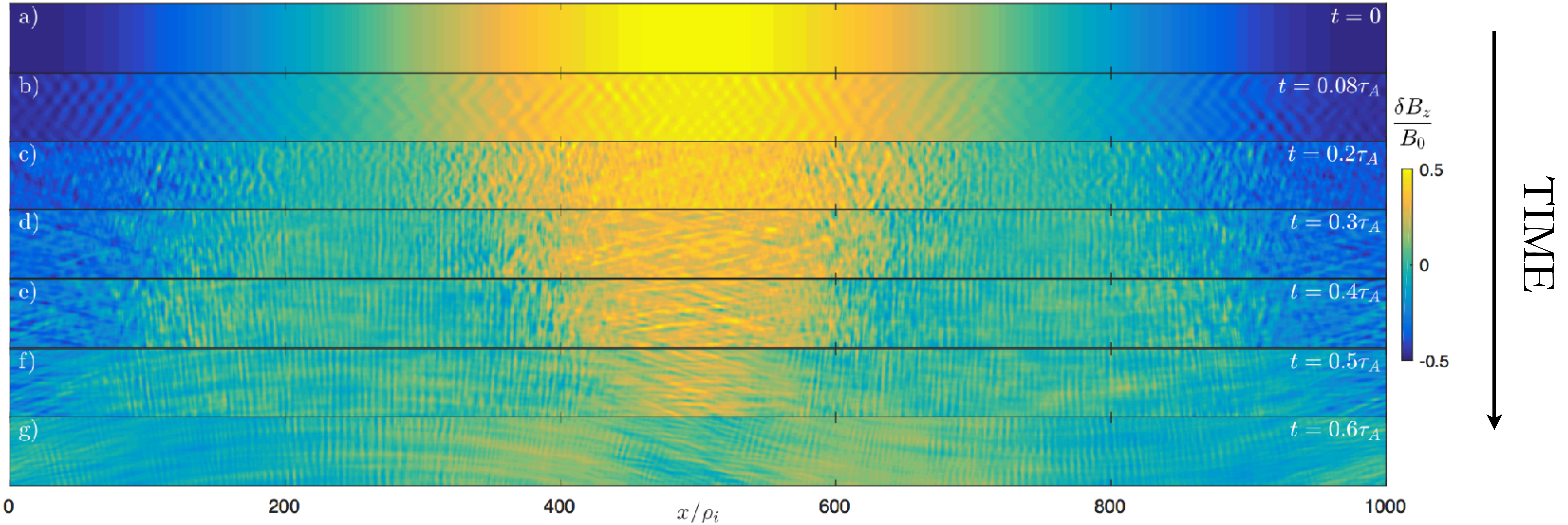
(3) On the average, the MRI produces positive pressure anisotropy, which is regulated by mirror and ion-cyclotron instabilities (*ab initio proof!*);

(4) Collisionless plasma acts like a high-Pm plasma, with a β-dependent effective viscosity. Beautiful energy spectra, with Alfvén-wave and kinetic-AW cascades.

(5) Despite prior theoretical work and an awareness of the issues involved,
I am *still* amazed that a collisionless turbulent plasma self-organizes to produce MHD-like behavior at large scales.

small adverts for some things I'm also excited about…

collisionless plasmas cannot support linearly polarized Alfvén waves above $\delta B_\perp / B_0 \sim \beta^{-1/2}$



Squire, Kunz, Quataert & Schekochihin, PRL, in press

Squire, Quataert & Schekochihin, 2016, ApJ, 830, 25